Improving On-Wafer CD Correlation Analysis Using Advanced Diagnostics and Across-Wafer Light-Source Monitoring

Paolo Alagna[a], Omar Zurita[b], Greg Rechtsteiner[b], Ivan Lalovic[b], Joost Bekaert [c],

a) Cymer LLC, Kapeldreef 75, 3001 Leuven, Belgium

b) Cymer LLC, 17075 Thornmint Court, San Diego, CA 92127

c) IMEC, Kapeldreef 75, B-3001 Leuven, Belgium

ABSTRACT

With the implementation of multi-patterning ArF-immersion for sub 20nm integrated circuits (IC), advances in equipment monitoring and control are needed to support on-wafer yield performance. These in-situ equipment monitoring improvements, along with advanced litho-cell corrections based on on-wafer measurements, enable meeting stringent overlay and CD control requirements for advanced lithography patterning. The importance of light-source performance on lithography pattering (CD and overlay) has been discussed in previous publications.[1-3] Recent developments of Cymer ArF light-source metrology and on-board monitoring enable end-users to detect, for each exposed wafer, changes in the near-field and far-field spatial profiles and polarization performance, [4-6] in addition to the key 'optical' scalar parameters, such as bandwidth, wavelength and energy. The major advantage of this capability is that the key performance metrics are sampled at rates matched to wafer performance, e.g. every exposure field across the wafer, which is critical for direct correlation with on-wafer performance for process control and excursion detection.

In this work, we present a new technique for characterizing patterning impacts due to controlled changes in light-source optical parameters. This technique provides a significant improvement in characterization of patterning sensitivity and allows decoupling contributions from other process or equipment. Wafer patterning experiments have been carried out in imec facilities, using an XLR660i laser and NXT:1950i ASML scanner, with controlled changes to bandwidth, wavelength and energy performance within the wafer. The changes in patterning performance are characterized using scatterometry and top-down CD SEM, showing excellent correlations between light-source data and on-wafer CD and CD uniformity for typical patterning geometries for ~40nm half-pitch. The characterization technique discussed in this paper significantly improves the correlation quality between the light-source data and wafer patterning by increasing the measurement signal-to-noise. Finally, this paper discusses the requirements for improved light-source control for further shrink extensions of multiple-patterning ArF immersion lithography.

KEYWORDS: Excimer Laser, Bandwidth, Wavelength, Energy, Proximity Control, Optical Lithography, Focus, Dose, Resolution

1. INTRODUCTION

ITRS technology roadmaps [7] show that ArF-immersion lithography solutions will continue to enable lithography patterning until EUV is fully adopted across patterning technologies. ArF-immersion multiple patterning with SMO (source-mask optimization), is considered complimentary to EUV to enable the definition of critical sub-20 nm technology.

The work we presented last year at the SPIE Advanced Lithography Conference[6], showed that near and far field beam characteristics can impact 1D patterning performance, as measured by the new laser on-board metrology developed by Cymer. This metrology enables monitoring near and far field beam performances (pointing, divergence) in addition to the polarization. In the same paper we showed pupil changes and on-wafer patterning impacts induced by controlled beam changes. The on-board metrology is part of the Cymer SmartPulse™ data product which additionally enables reporting key optical parameters, such as bandwidth, wavelength and energy per every exposure field on-wafer. This capability enables the direct characterization of patterning response on-wafer and comprehensive light source performance monitoring.

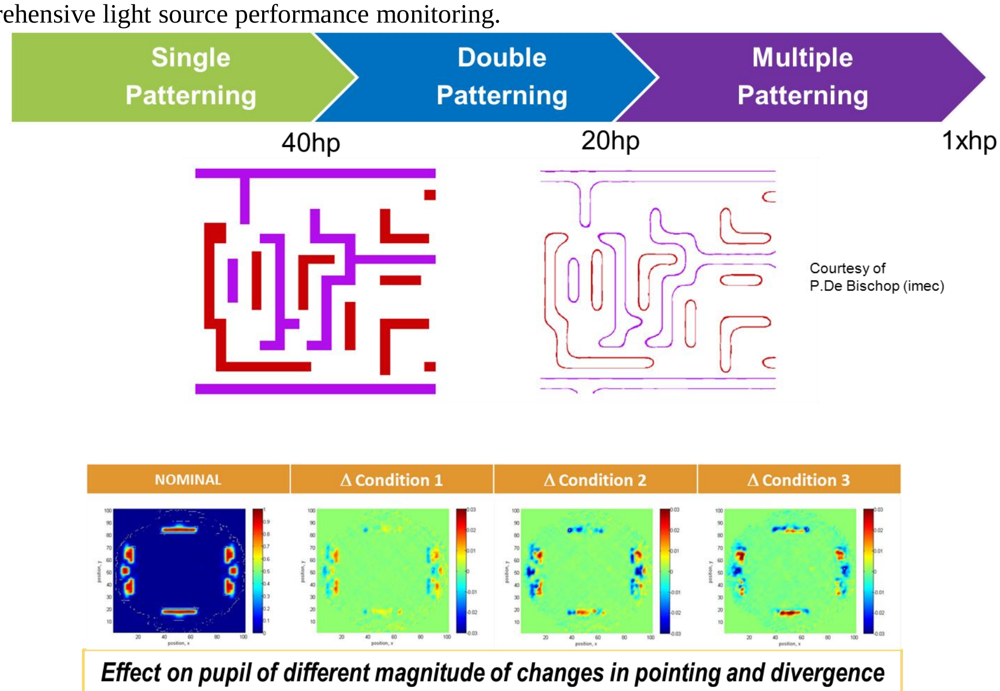

Figure 1. ITRS Summary of patterning transitions by half-pitch, example of multiple patterning logic layouts, and pupil response to laser induced changes [6].

Previous experimental results showed the importance of understanding of the ArF source impact on patterning performance during wafer exposure to ensure process stability. In order to enhance the characterization of specific patterning layer response, Cymer has developed an advanced technique which allows field level modulation of bandwidth, wavelength and dose stability across the wafer. This technique enables obtaining an accurate on-wafer response of 1D and 2D patterns to changes in laser performance, achieving a significant improvement in measurement signal to noise by removing the contribution of wafer-to-wafer measurement errors.

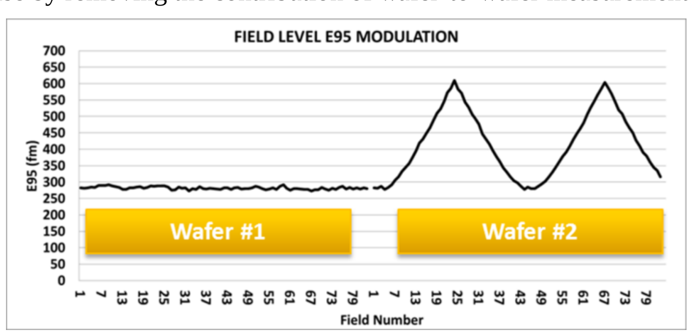

Figure 2. Example of Nominal Wafer Exposure (Wafer #1) and Field-to-field Laser Bandwidth E95 Modulation (Wafer #2)

2. PROCESS SENSITIVITY CHARACTERIZATION

The experimental activities reported in this paper were performed on the XLR 660ix laser feeding the NXT:1950i ASML scanner, installed in imec's 300mm facility. This system is interfaced with the Cymer SmartPulse^{TM} data product enabling per wafer and per field data for light-source performance obtained during the actual exposure of test wafers. The response to changes in bandwidth (E95) of 1D patterns with different line-width and pitch combinations was investigated first. Two sets of wafers were exposed: the first one at nominal bandwidth (300 fm), while the exposure of the second one is characterized by a change in E95 from nominal up to 600 fm. The bandwidth changes are modulated per exposed field, following a set of programmed set-points as described in Table 1.

Given that the imec infrastructure offers several different advanced metrology solutions, our selection has been made considering that we wanted to achieve high density of across wafer sampling, including intra-field (104 points per each 26mm x 33mm exposure) across the entire wafer (83 fields). Considering the high measurement density, we decided to use the scatterometry system (ASML YS-200), which is capable to achieve up to 107 measurements per minute (one pitch and one orientation) per wafer sample within reasonable tool time. Table 1 also includes the selection of the CD/pitch combinations. The process for the exposure of the scatterometry targets was already defined by imec : JSR AIM5484 resist at 105nm and the annular source with 1.35 NA, inner sigma of 0.79, outer sigma of 0.84 . The first scheduled test was conducted, modulating bandwidth (E95) across the wafer. Starting from nominal condition, each field has been exposed with a different setting.

TARGET CD
Mask Pitch 84nm CD 39 → Wafer CD 41nm
Mask Pitch 92nm CD 45 → Wafer CD 47nm
Mask Pitch 128nm CD 62 → Wafer CD 49nm
Mask Pitch 200nm CD 84 → Wafer CD 49nm
Note : No assist features

METROLOGY
Scatterometry (ASML-YieldStar 200)
Measurements per wafer : 8.632
(one pitch and orientation)

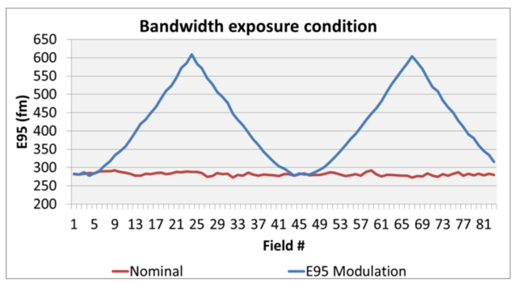

Table1. Measurement targets and exposure condition

The response of the four selected targets in Figure 3 shows, as expected, that the most contrast sensitive patterns (pitch 128 and pitch 200) exhibit a much higher CD response [1-3] to changes in laser bandwidth. This first test shows the importance of field level data collection; the dashed line in Figure 3 shows the average wafer CD of the modulated wafer from the CD average of the nominal wafer. The histogram bars, on the other hand, show the CD differences per field between the nominal wafer condition and exposures where field-level changes in E95 were present. From these plots it is immediately clear how important field level data is to enhance the yield control capability. This figure shows also the direct correlation between the bandwidth changes achieved per field and impacts on different type of 1D pattern on wafer.

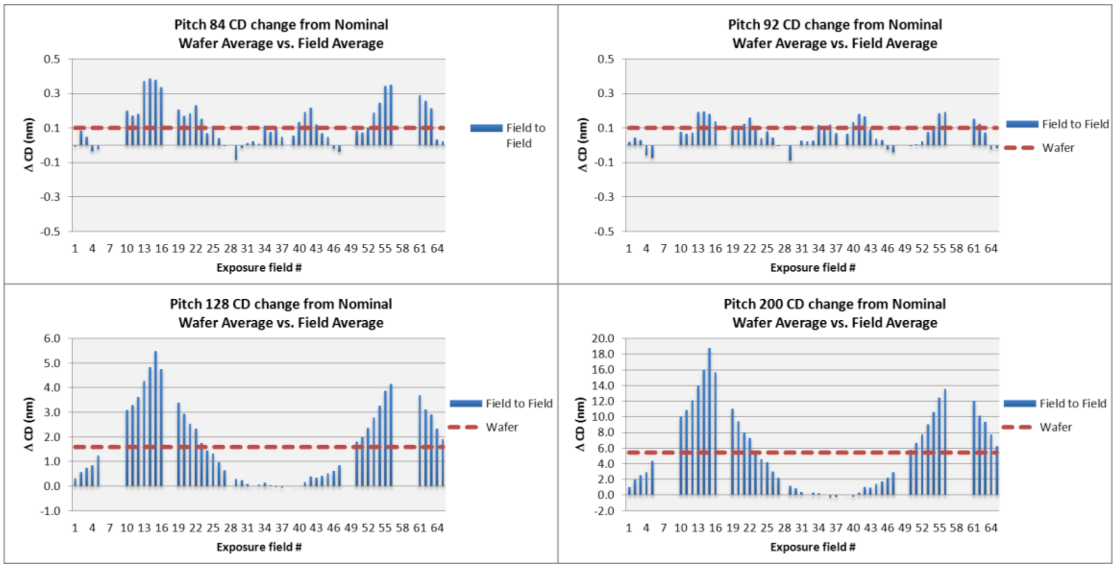

Figure 3. Field to field CD response to bandwidth changes. Difference from nominal condition. Edge field removed.

Characterization of 1D pattern response by changing laser bandwidth performance per exposure field confirms the quadratic response for all CD-pitch combinations, as has been already reported in previous work [1-3]. Additionally this analysis can be used to qualify the precision of laser bandwidth data reporting, which shows excellent agreement with scatterometry on-wafer measurements, with R^2 exceeding 0.99 for the most sensitive pitches (pitch 128nm and 200nm).

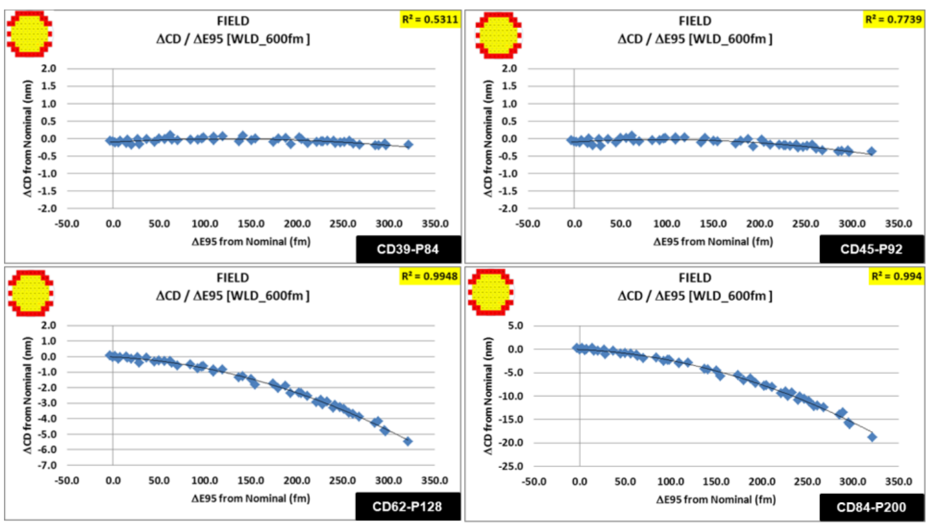

Figure 4. Different line-width/pitch combinations show a common trend.

We also quantified the changes in line-width roughness induced by optical parameter's changes. Contrast changes, as induced by variation of laser bandwidth, is only one of the factors which can contribute to changes in pattern roughness, and the interactions are indeed more challenging to investigate than simply the line-width CD response. We applied the same approach to vary the laser bandwidth performance across the wafer to directly quantify the roughness response through a range of different E95 performance levels. The investigation of the line-width roughness response has been conducted on a different reticle enabling lines and spaces that can be also cleaved for cross-section analysis. An optimized source, which improved the overall roughness, has been also implemented (x-polarized, dipole 40 degree, Y orientation with 1.35 NA, inner sigma of 0.70, outer sigma of 0.80). Figure 5 shows an example of what was the response to a pattern with a line-space rate of 1:2. The measurements were executed by the CD-SEM Hitachi CG5000.

In the left-hand graph in Figure 5, the change in line-width roughness also follows a 2nd order polynomial fit to bandwidth E95 performance; this is consistent with an excellent paper on resist characterization published previously[8].

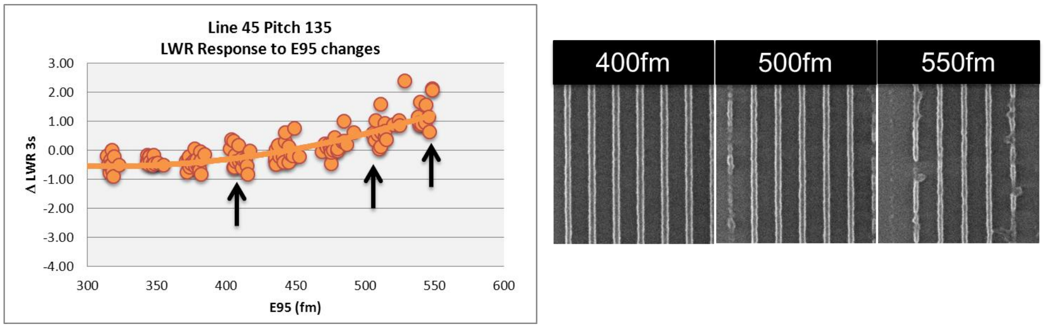

Figure 5. LWR Change as Function of Different E95

The per field changes in laser performance have been applied to experimentally measure the pattern response to additional laser optical parameters, including wavelength and energy stability. Figure 6 shows the summary of the laser actuation conditions and wafer patterning results.

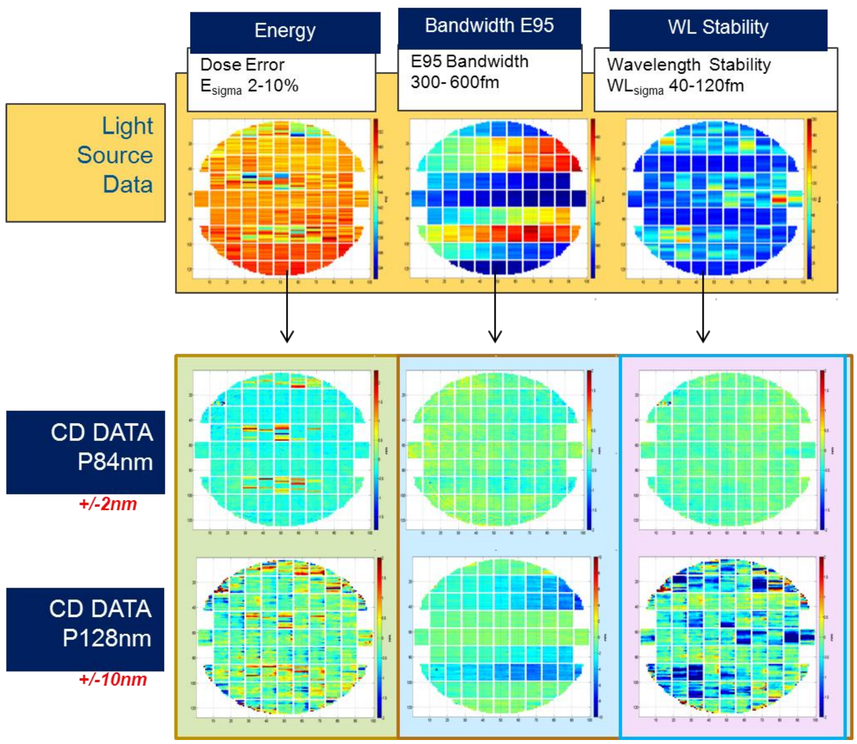

Figure 6. Across-wafer 1D Pattern response to per-field modulation of optical laser parameters

The methodology applied here demonstrates that the response of 1D pattern is well correlated to programmed changes in laser parameters across the wafer.

We also investigated the more complex response that results from 2D patterns, which are more representative of the response of actual device features. We selected to use as reference the first split of a double patterning 14nm logic Metal 1 process layer, which is part of one of imec's process development test vehicles. The response of three different types of patterns has been measured for this part of the experiment. Our attention was particularly dedicated to the response of the critical hotspots and tip-to-trench and tip-to-tip structures. Wafer samples were prepared with a stack made by 100 nm of SOC (Spin On Carbon) and 40 nm of SOG (Spin on Glass), then coated with 100 nm of Fujifilm M190 resist (negative tone development process), using an optimized freeform source.

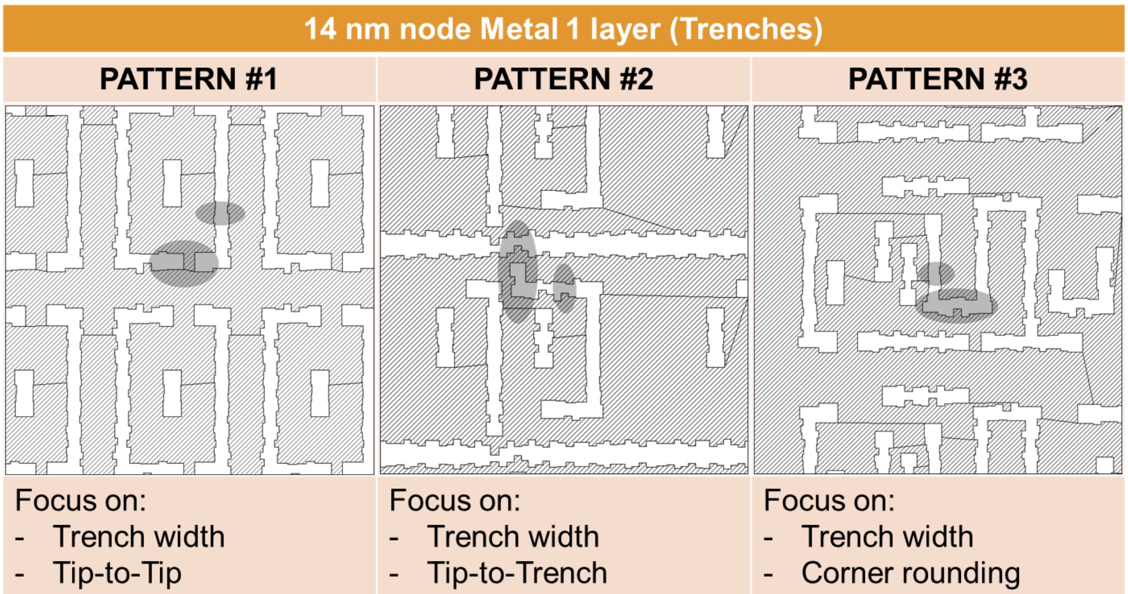

Figure 7.2D Mask Pattern Layouts Selected from imec double-patterning 14nm logic Metal 1 layer (first split)

The pattern sensitivity study on 2D structures requires a more structured approach[9,10]; the analysis has been focused then in different areas:

a. 1D trench width measurement distribution

b. 2D critical features changes

c. Contour analysis

d. Defect density analysis

Critical dimension measurements were performed on Hitachi CG5000 CD-SEM. Each value reported in the plots is the average of 4 identical patterns located in the exposure field.

2.1 1D cut-line-measurement change

The trench width measurements from 2D layouts can lose part of the predictability characteristics, unlike to what has been seen in the 1D structure [Figure 4].This is mainly caused by the fact that the pattern definition could be somehow modified by the optical proximity interactions with other patterns (lines or line ends), OPC corrections and mask-writer errors. Figure 7 shows the measurement change of a single orientation line width in a complex 2D structure mainly keep the same quadratic response as shown in the L/S 1D pattern measured using scatterometry previously.

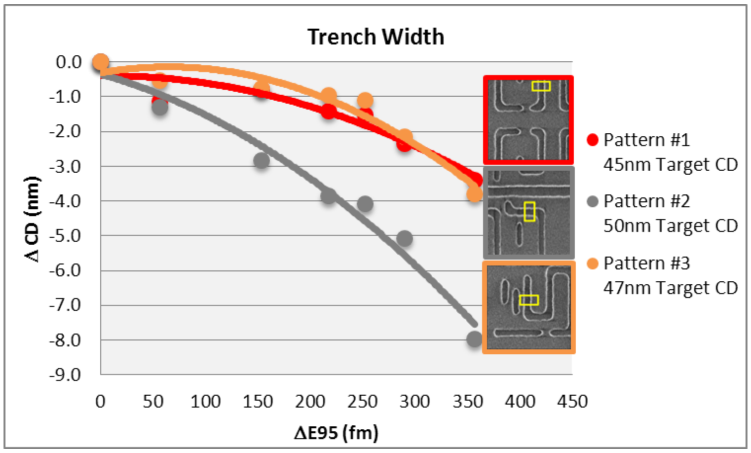

Figure 7. Trench width measurement changes at different bandwidth conditions

The target CD for these features (after etch) is approximately 32 nm, so if we assume a 10% CD error tolerance, the litho specification on the CD is ± 3.2 nm. In this scenario, bandwidth changes in the range of 100fm can contribute to a significant part of the total available budget for Metal 1 patterns.

2.2 Tip-to-tip and tip-to-trend measurement changes

2D patterns offer indeed a much wider combination of critical features with respect to the single orientation pattern. The measurement of the distance between two opposite line ends (tip-to-tip) or between a line-end perpendicular to a trench (tip-to-trench) were also obtained as function of different bandwidth. Plotting the tip-to-trench or tip-to-tip distance (or gap) for each change in bandwidth (from nominal 300fm) (Figure 8), it is evident that the sensitivity of line-ends can be much more unpredictable.

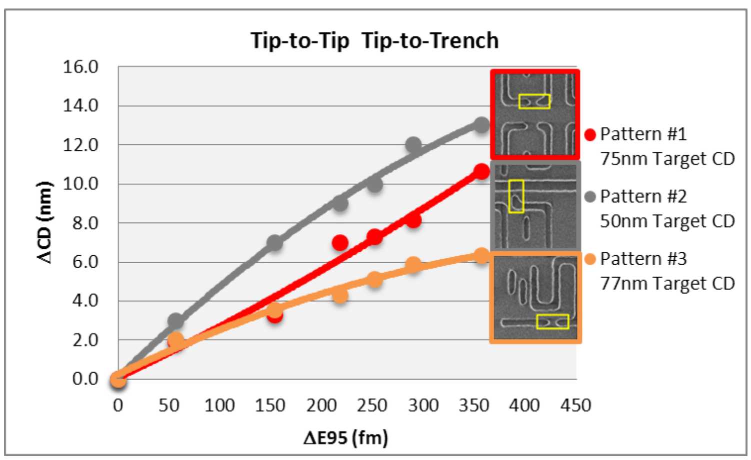

Figure 8. Tip-to-Tip and Tip-to-Trench measurement changes at different bandwidth conditions

Trying to define the best analysis approach in cases like the one we are considering, has been decided to plot the ratio between measurement changes in GAPS (tip-to-line or trench) and TRENCH WIDTH as function of different bandwidth (E95) variations. As reported in the results summarized in the following figure the sensitivity of line-ends can be up to 4 to 5 times higher compared to single orientation trench-width measurement for Metal 1 patterning.

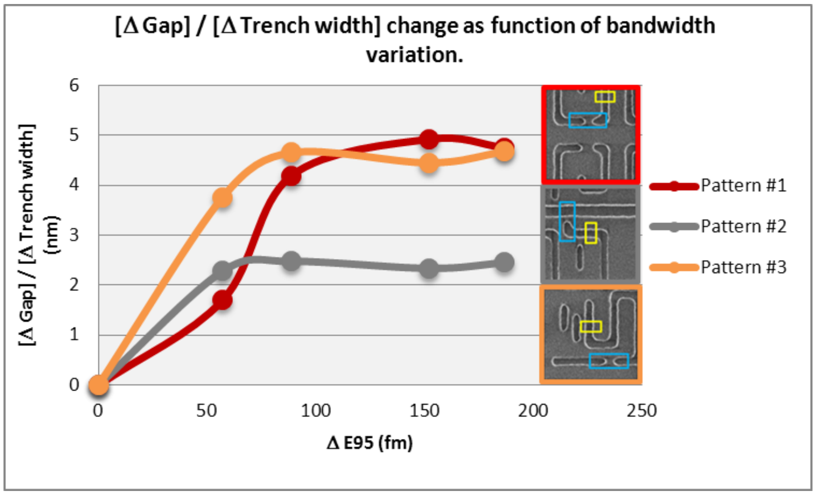

Figure 9. Correlation between changes in the gap distances and trench width as function of E95 change

2.3 Contour analysis

The characterization of 2D patterns is indeed challenging because the complexity of the process factors related to such structures (OPC, process stack, proximity, hotspots, etc.) leave even to the most advance stochastic approach an important margin of uncertainty. In our experiment we have chosen to analyze those critical features also by using contour analysis of SEM measured patterns. We used the capability available in the Hitachi Hi-frame platform to superimpose the measured contours with the reticle design file (GDS). We averaged four measurements per field at the same laser bandwidth condition, and the extracted contour results are shown in Figure 10.

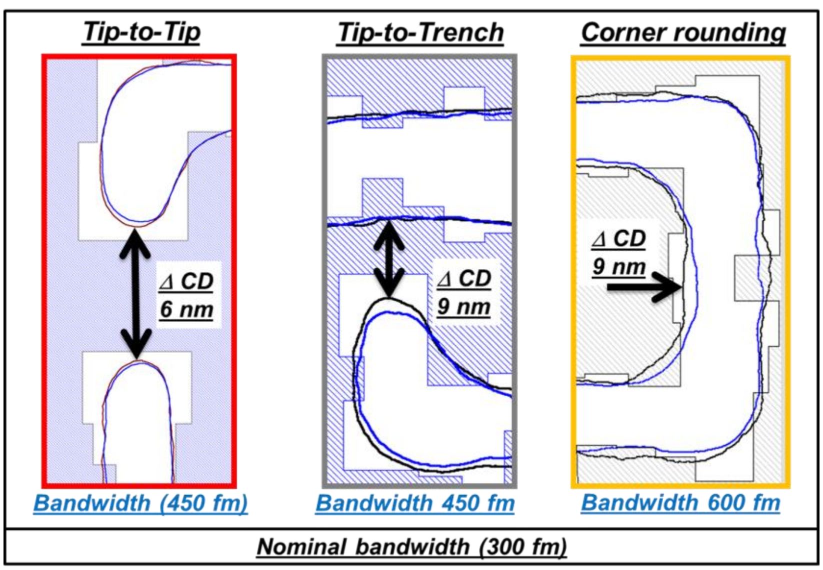

Figure 10. Contour Analysis of Experimental CD contours using Hitachi Hi-frame

Even though maximum changes allowed for the tip-to-tip and tip-to-trench would be larger (imec specifies 9nm and 6nm control respectively); as shown, the maximum laser E95 excursion up to 600fm would significantly exceed the allowed performance of trench-ends. No specific criteria are defined for the corner rounding, however the impacts due to contrast loss can clearly impact 2D layout critical areas.

2.4 Defect density analysis

We also carried out a defect density analysis to determine the potential impact of bandwidth change on 2D structures. Using KLA 2825 optical inspection tool we inspected the field area where the different modules selected in this experiment where located resulting in an overall scanning area of 69.69 cm^2 (57 exposure fields scanned). Our objective was to benchmark the defect density distribution of 4 different exposure conditions: Nominal (reference) bandwidth wafers, 300fm to 600fm of E95 bandwidth per-field modulation across the wafer (labeled BW1), Nominal bandwidth and 2% of dose error (fixed in all wafer), Nominal bandwidth and large dose error (> 20%). Multiple wafers were exposed, including four reference wafers and two wafers per experimental condition, to obtain a measure of the wafer-to-wafer reproducibility. Figure 10 shows that the defect density (total defect count per 69.69 cm^2 area) increases by as much as 25 times for the wafers exposed with bandwidth modulation compared to the Nominal wafer exposures. The additional dose error conditions increase the defect density further, as expected.

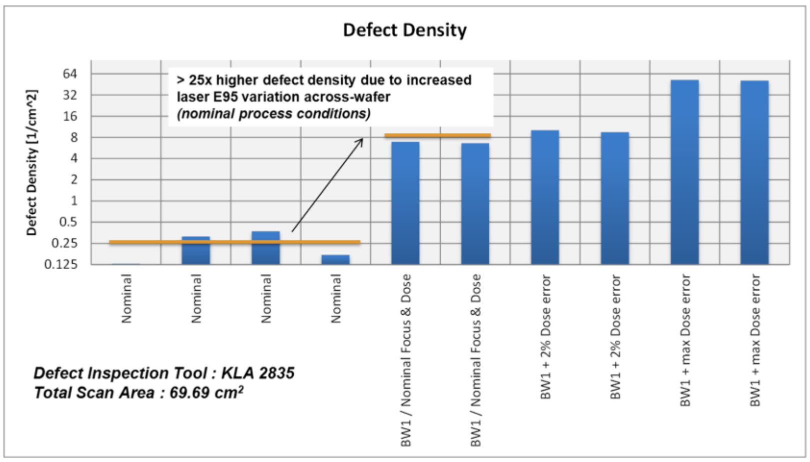

Figure 11. Defect Density as a Function of Different Experiment Conditions

3 ADVANCE SOURCE MONITORING CAPABILITIES

Given the implementation of multiple patterning, advances in equipment monitoring and control are needed to support on-wafer yield and process development cycle-time. In previous work[4-6], the Cymer Smartpulse™ platform capabilities have been described in order to meet the needs of advanced lithography patterning control. This capability is used by chipmakers to enhance equipment monitoring, providing key light-source performance data for each exposed wafer. SmartPulse ™ enables direct correlation of light source performance with wafer exposure data, and includes per field sampling-rate data for key optical parameters (bandwidth, wavelength and energy). As shown in this paper, per field sampling and high level of metrology precision (quality) is required for accurate correlation and determination of patterning impacts.

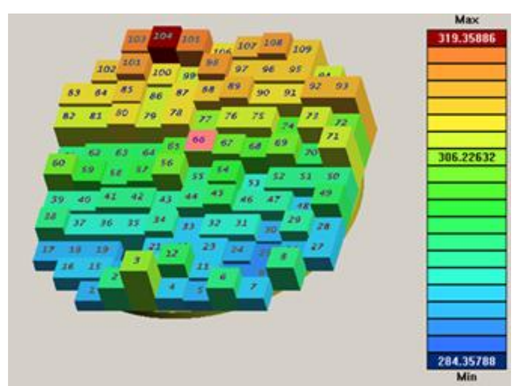

Figure 11. SmartPulse™ Field-level Wafer Exposed Data

4 CONCLUSIONS

The on wafer impact of light source optical parameters modulation have been characterized using an advanced laser experiment at imec's facilities in Leuven (BE). This technique allowed us to measure the lithographic response of 1D patterns with different line-width and pitch combinations, through field level modulation of wavelength, dose error and bandwidth (E95). The results obtained are consistent with what has been reported in the literature [1-3] showing a quadratic correlation between bandwidth and line-width change; roughness changes showed also a similar response. The same approach has been used to characterize wafer patterning performance to E95 changes, on three samples of the first split of a double patterning 20nm logic Metal 1 process layer. Despite the trench-width measurements were consistent with the expectations, it must be taken into account that in the examples considered, due to the optical proximity interactions with other patterns (lines or line ends), OPC corrections and mask-writer errors the predictability is not as clear as in the 1D pattern. With the technique adopted it was also possible to study the overall 2D pattern modification to E95 changes. In particular our study showed how the distance change between two opposite trench ends (tip-to-tip) or between a trench-end perpendicular to a trench (tip-to-trench) can be up to 4 times higher than the critical line-width present in the same structure, when a deviation of 100 fm from nominal bandwidth condition, is measured. Observing the results change we could conclude that 150 fm of E95 change from standard working conditions can significantly compromise the yield, causing remarkable changes in the trench-width and trench-ends patterning results. Defect analysis showed that the defect density on wafers where the bandwidth field level modulation has been applied, if up to 25 times higher than wafers exposed in nominal condition. In this experiment we have also demonstrated that per field sampling and high level of metrology precision (quality) is required for accurate correlation and determination of patterning impacts and that SmartPulse™ enables direct field level correlation of light source performance with patterning data, for key optical parameters.

ACKNOWLEDGEMENTS

The authors are very grateful for all support given to this project. In particular,Remo Petrella of Cymer, Koen D'Havé, Peter De Bisschop, Jing Wang, Wouter Pypen, Frieda Van Roey of imec, Kei Sakai, Daisuke Fuchimoto from Hitachi, Yves Belien, Charles Schaap together with all ASML on-site support team in imec, are acknowledged for their help, practical discussions and organizational support.

REFERENCES

[1] U. Iessi ed al. "Laser bandwidth effect on overlay budget and imaging for the 45 nm and 32nm technology nodes with immersion lithography", Proc. SPIE 7973, Optical Microlithography XXIV, 797328

[2] N. Seong, et al. "Analysis of the effect of laser bandwidth on imaging of memory patterns", Proc. SPIE 7140, Lithography Asia 2008, 714042

[3] P. De Bisschop et al. "Impact of finite laser bandwidth on the CD of L/S structures", Journal of Micro / Nanolithography, MEMS and MOEMS (JM3), Vol. 7, No. 3 (2008)

[4] T. Cacouris et al. "Advanced light source technologies that enable high-volume manufacturing of DUV lithography extensions" SPIE Proc. Vol. 8326 (2012)

[5] J.Choi et al., "Enhancing lithography process control through advanced, on-board beam parameter metrology for wafer level monitoring of light source parameters", Proc. SPIE Optical Microlithography XXV 8326,99 (2012).

[6] P.Alagna et al., "Lithography imaging control by enhanced monitoring of light source performance",Proc. SPIE Optical Microlithography XXVI 8683,28 (2013)

[7] ITRS, International Technology Roadmap for Semiconductors [www.itrs.net]

[8] Pawloski et al., "Characterization of line edge roughness in photoresist using an image fading technique", Proc. SPIE Optical Microlithography XXI, 5376-44 (2004)

[09] K. Iwase et al. "A new source optimization approach for 2X node logic" , Proc. SPIE. 8166 Photomask Technology 2011

[10] J. Bekaert et al. "Freeform illumination sources : an experimental study of source-mask optimization for 22-nm SRAM cells" Proc. SPIE 7640, Optical Microlithography XXIII, 7640,08 (2010);

http://spie.org/AL/conferencedetails/optical-microlithography